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Abstract

The azimuthal dependence of the flow of hadronic energy about the momentum transfer direction in charged-current deep-inelastic neutrino-nucleon scattering is used to study gluon emission and the transverse momentum $\langle k_T \rangle$ of partons confined inside the nucleon. The data were taken at Fermilab using a 340 ton fine grained calorimeter exposed to a narrow band neutrino beam. A seven standard deviation azimuthal asymmetry is observed indicating an average $\langle k_T \rangle = 0.303 \pm 0.041$ GeV/c.

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In this report we consider the asymmetry of the flow of hadronic energy around the momentum transfer direction, which measures the transverse momentum of the struck quark[1], k_T, and provides a complementary test of perturbative QCD[2,3]. Such a study has been performed in muon-nucleon deep-inelastic scattering[4]. Analyses of the hadronic shower asymmetry have also been performed in neutrino bubble chamber experiments[5], but the data have limited statistics and a missing neutrals problem. Here we present a higher statistics measurement[6] from data taken at Fermilab using a fine-grained calorimeter[7] exposed to the narrow-band neutrino beam[8].

The presence of a hadronic shower asymmetry around the momentum transfer direction in deep-inelastic lepton-nucleon scattering was suggested by Georgi and Politzer[2] to be a test of perturbative QCD predictions. However, Cahn[1] noted that at present accelerator energies there is a large contribution to this asymmetry from the nonperturbative effect of k_T. We therefore analyze our data under two assumptions: (1) that there are only two jets in the final state corresponding to the struck quark and the recoil diquark system each with a finite k_T (2-jet case), and (2) that there are three jets corresponding to the struck quark and the diquark system as in the previous case plus a third jet associated with a radiated gluon (3-jet case). A nonperturbative k_T is included as in the the 2-jet case above. In both cases the k_T-distribution is assumed[9] to be an exponential in $(k_T)^2$.

Our neutrino detector[7] is a 200 metric ton (fiducial mass) flash chamber - proportional chamber calorimeter with 5.5 mm lateral segmentation (cell size) and 3 cm (corresponding to 0.25 of a radiation length and 0.03 of an absorption length) longitudinal shower sampling. The detector measures two orthogonal views of energy flow from which an azimuthal asymmetry is determined by considering the correlation between the hadronic energy flow direction and the neutrino-muon scattering plane. The local density of hit cells in the flash chambers is proportional to the local deposition of energy in the shower.

To measure the flow of hadronic energy around the momentum transfer direction we define the azimuthal angle φ_i for a single hadron referenced from the neutrino-muon scattering plane. Figure 1 shows the scattering process at the parton level. We expect that the observed hadrons from the fragmenting parton (hadronization) will be distributed symmetrically about the final state momentum of the parton. The hadron jet therefore roughly measures the parton direction. The quantity we will study is the energy weighted average value of $\cos\varphi_i$ given by:

$$\cos\varphi = \Sigma\ E_i\ \cos\ \varphi_i\ /\ \Sigma\ E_i, \qquad (1)$$

where E_i is the energy of the hadron i, and the summation is over all particles in the hadronic final state.

Our detector does not separately determine the energy of each primary hadron in the hadronic shower, but the energy weighting measurement given by eq. (1) follows naturally from the pattern of energy deposition in our calorimeter. We therefore estimate $\cos\varphi$ by considering the pattern of hit cells in each of the two flash chamber views. The details of the parton level physics, electromagnetic radiation corrections, hadronization, secondary interactions in the hadronic shower, and detector properties are included in the Monte Carlo simulation (MC). By comparing the Monte Carlo with the data, the k_T and QCD effects are determined. This method uses all data without preselection for any asymmetrical φ distribution, i.e. no cuts on oblateness or sphericity.

The measured $\cos\varphi$ distribution for all of the ν data is shown in Figure 2. [We consider only the ν data (9200 accepted charged-current events) in this paper since the $\bar{\nu}$ data (1800 events) are of limited statistics.] The plot is folded to emphasize that the mean $\langle\cos\varphi\rangle = -0.0224 \pm 0.0032$ (statistical error) of the distribution is small compared to the width, but the asymmetry is not dominated by a few events in the tails of the distribution.

Since the mean of the cos φ distribution is so small in comparison with its width, a thorough knowledge of the systematic errors is important. We investigated the following sources of systematic error in $\langle\cos\varphi\rangle$: proper

identification of the muon track (±0.0004); removal of leptonic energy deposition (±0.002); shower containment (±0.0005); and bias in the determination of the momentum transfer direction (±0.0005). The total systematic error, $\delta_{<\cos\varphi>} = 0.0022$, is determined from the above contributions added in quadrature.

The azimuthal asymmetry from k_T (2-jet case) arises from the kinematical effect that the magnitude of the neutrino-parton scattering cross section depends on s, the square of the center-of-mass energy of the neutrino-parton scattering. Cahn[1] has shown that s depends on the orientation of k_T with respect to the incident neutrino-outgoing lepton scattering plane[10]. This dependence on the direction of k_T gives rise to an enhancement of events where the target jet lies between the outgoing lepton and the current jet ($<\cos\varphi> < 0$). At the parton level in leading order for $Q >> k_T$ the expected value of $\cos\varphi$ in eq. (1) is :

$$\cos\varphi = -(k_T(x)/Q)\ (1-y)^{\pm 1/2}, \qquad (2)$$

where +(-) refers to neutrino (antineutrino)-quark scattering, $k_T(x)$ is the transverse momentum of the struck parton with respect to the momentum transfer direction, which we allow to be a function of x, the Bjorken scaling variable, Q is the magnitude of the 4-momentum transfer from the neutrino to the nucleon and is measured by the reconstructed incident neutrino energy and the outgoing muon momentum, and $y = E_h/E_\nu$ where E_h is the measured hadronic energy, and E_ν is the reconstructed incident neutrino energy. At the parton level (before hadronization) this kinematical effect produces an asymmetry $<\cos\varphi> \approx -0.1$ for $<k_T> = 0.3$ GeV/c in the energy range of this experiment.

An azimuthal asymmetry arises from gluon radiation[3] (3-jet case) as well as from the parton k_T (2-jet case) discussed above. First-order QCD introduces a third forward jet from gluon emission which is usually soft in comparison with the current jet. An interference between gluon emission from initial and

final parton lines enhances events where this soft jet lies between the outgoing lepton and the current jet. The QCD radiative effects predict[3] to leading order an asymmetry at the parton level given by:

$$\cos\varphi = -\alpha_S(Q^2) \quad f(x,Q^2) \quad (1-y)^{\pm 1/2}, \tag{3}$$

where the ± sign convention is the same as above, $\alpha_S(Q^2)$ is the strong interaction coupling constant, Λ is the QCD scale parameter and is set to 0.3 GeV/c throughout this work[11], and $f(x,Q^2)$ is a convolution integral over the nucleon structure functions. The Q^2-dependence in eq. (3) is predominantly in the $\alpha_S(Q^2)$ term. The QCD asymmetry before hadronization in the energy range of this experiment is expected to be $\langle\cos\varphi\rangle \approx -0.1$, which, as Cahn noted[1], is about the same size as the asymmetry expected from k_T.

The QCD calculation contains divergent terms associated with zero-energy jets and nonzero-energy collinear jets both of which can be treated theoretically[12]. For our MC we have computed the gluon radiation of the 3-jet production to follow the analytic form as nearly as possible while avoiding the divergent regions. This was achieved by requiring that all events contain three jets with a cut on the gluon spectrum to keep the inclusive cross section fixed to the analytic value. Furthermore the energy weighting algorithm of eq. (1) tends to reduce the contribution of the divergent regions.

The parton level asymmetry is significantly reduced by the hadronization of the struck parton into primary hadrons and the secondary interactions of the primary hadrons in the first stage of the shower development[13]. We find by our MC program a reduction of a factor of five resulting in an expected $\langle\cos\varphi\rangle \approx -0.02$ for $\langle k_T\rangle = 0.3$ GeV/c with the QCD gluon emission effects.

Having measured a significant shower asymmetry we now extract the value of k_T under our two assumptions. By fitting $\langle\cos\varphi\rangle$ averaged over all events under the assumption that k_T is constant with respect to x, we find that $\langle k_T\rangle = 0.443 \pm 0.031$ GeV/c in the 2-jet case, and $\langle k_T\rangle = 0.303 \pm 0.041$ GeV/c in the 3-jet case, where we have assumed $\Lambda = 0.3$ GeV/c for 4 quark flavors.

Figure 3 shows the measured asymmetry $\langle\cos\varphi\rangle$ for our neutrino data plotted as a function of y. (The other kinematic variables have been integrated.) The data are consistent with $\langle\cos\varphi\rangle \to 0$ for $y \to 1$ as expected from both the parton k_T term and the QCD term given by eqs. (2) and (3), respectively.

The best variable with which to separate the k_T from the first order QCD effects is Q^2. The k_T term (eq. 2) varies as $1/Q$, while the 3-jet term (eq. 3) varies logarithmically with Q^2 through the QCD coupling term $\alpha_S(Q^2)$. Figure 4 compares the measured $\langle\cos\varphi\rangle$ as a function of Q with the 2-jet and 3-jet MC simulations given in curves (a) and (b) of the figure, respectively. As we would expect, the data are better simulated by the 3-jet case - where both the k_T and the QCD effects are operative, than by the 2-jet case - where the asymmetry arises from k_T only. The χ^2/(degree of freedom) for curve (a) (curve (b)) is 4.88 (1.82). The statistical and systematic errors are approximately equal and have been combined in quadrature in the quoted error.

To investigate the x-dependence of $k_T(x)$ we have set $k_T(x)=bx$, where b is a constant as suggested by covariant parton models[14]. By fitting the data with the requirment that the global average $\langle\cos\varphi\rangle$ be held constant, we find that in the 2-jet (3-jet) case a good fit is obtained with $b=1.94 \pm 0.14$ GeV/c ($b=1.33 \pm 0.18$ GeV/c). The corresponding values of k_T are $\langle k_T\rangle = 0.426 \pm 0.030$ GeV/c and $\langle k_T\rangle = 0.292 \pm 0.039$ GeV/c for the 2-jet and the 3-jet case, respectively. The effect of this x-dependence on the Q-dependence is shown in Fig.4, curve (c) where χ^2/(degree of freedom) =1.14, and curve (d) where χ^2/(degree of freedom) =1.23. The agreement of theory and data is seen to be better than that of curves (a) and (b) where no x-dependence was assumed, but with this x-dependence there is little distinction between the 2-jet and the 3-jet cases. We note that the y-dependence shown in Fig. 3 is unaffected by allowing $k_T=bx$.

In summary we have found a statistically significant asymmetry in the azimuthal distribution of hadronic energy in deep-inelastic charged-current

neutrino-nucleon scattering. We interpret this to originate from the intrinsic transverse momentum of partons confined in the nucleon with a mean $\langle k_T \rangle = 0.303 \pm 0.041$ GeV/c if gluon emission is included, or $\langle k_T \rangle = 0.443 \pm 0.031$ GeV/c with no gluon emission. These values are smaller than those measured by references (4) and (5). Our data suggest that $\langle k_T \rangle$ is dependent on x since the quality of the fit is improved, although when $k_T = bx$ there is little distinction between the 2-jet and the 3-jet case. We are analyzing a larger and higher energy data sample which will significantly improve our measurement by allowing the k_T contribution to be more cleanly separated from the QCD gluon emission effect, and the x-dependence of k_T to be more carefully studied.

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[9] We have checked that the results do not depend on the explicit form of the k_T distribution. (A. Mukherjee, Thesis, ibid.)

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Figure Captions:

Figure 1. The event geometry is shown where the incident neutrino and outgoing muon momentum vectors define the lepton scattering plane, and the $W^{\pm}$ direction and the momentum vector of the struck parton define the hadronic plane. The azimuthal angle φ at the parton level is defined from the lepton plane as shown. Note that $\varphi_i \approx \varphi$ where φ_i is the azimuthal angle of hadron i which fragments from the struck parton.

Figure 2. Shown is a histogram of the measured $\cos\varphi$ of all the ν-data with the negative half of the distribution folded onto the positive half. The arrow marks the mean of the distribution, $\langle\cos\varphi\rangle = -0.0224$, folded onto the positive axis.

Figure 3. The mean $\langle\cos\varphi\rangle$ of all of the ν-data is plotted versus y in equal statistics bins. The combined statistical and systematic errors are displayed. The expected y-dependence is seen. Since there is little difference between the calculated 2-jet and 3-jet asymmetries as a function of y, we show only the average of the two theoretical assumptions using the k_T values determined above.

Figure 4. The mean $\langle\cos\varphi\rangle$ is plotted versus Q for all the ν-data in equal statistics bins. Curve (a) indicates the fit of the 2-jet Monte Carlo with no x-dependence. Curve (b) shows the result of the 3-jet calculation. Curve (c) is the 2-jet case, but with k_T linearly dependent on x. Curve (d) is the 3-jet case with k_T linearly dependent on x.

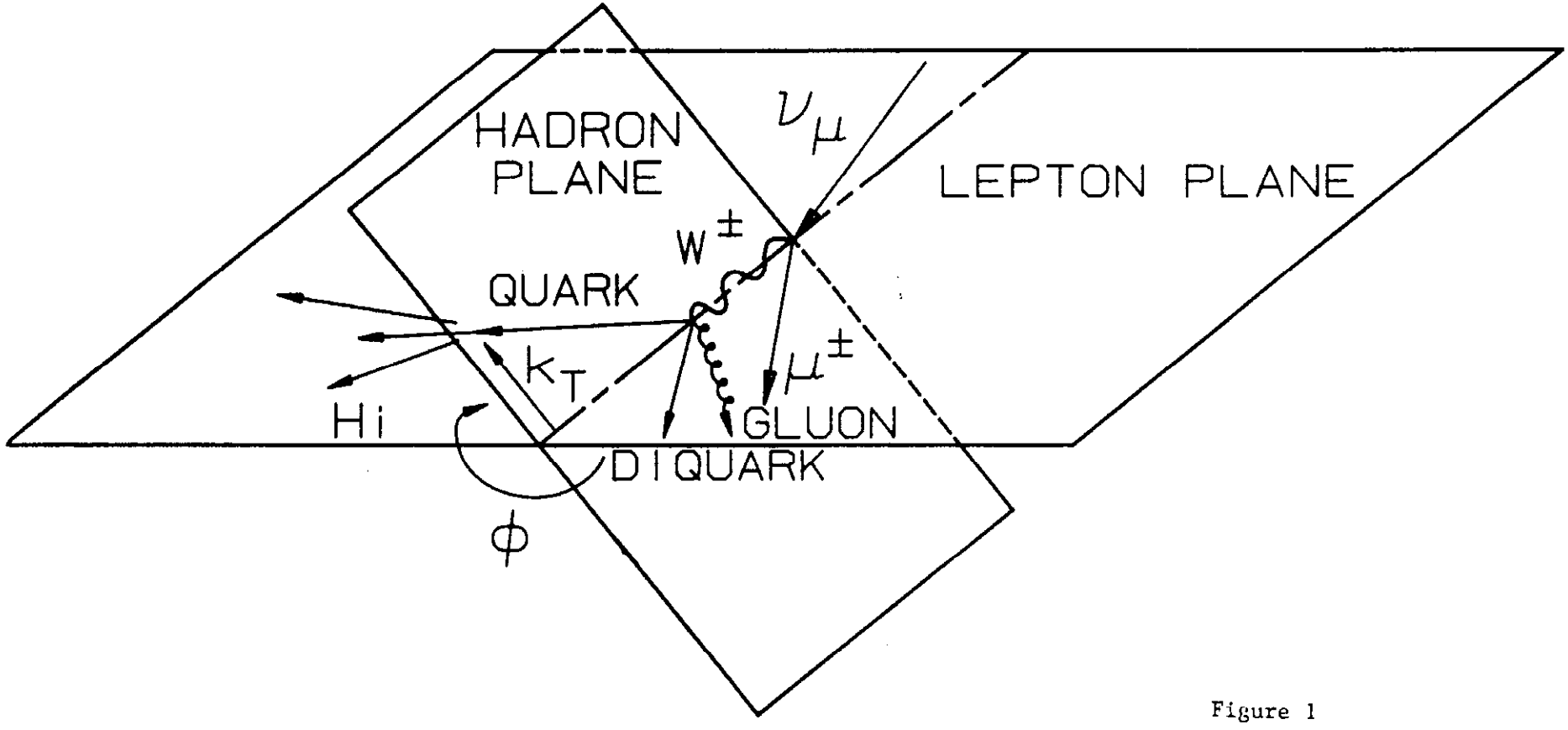
HADRON
PLANE
ν_μ
LEPTON PLANE
$W^\pm$
QUARK
k_T
$\mu^\pm$
Hi
GLUON
DIQUARK
ϕ

Figure 1

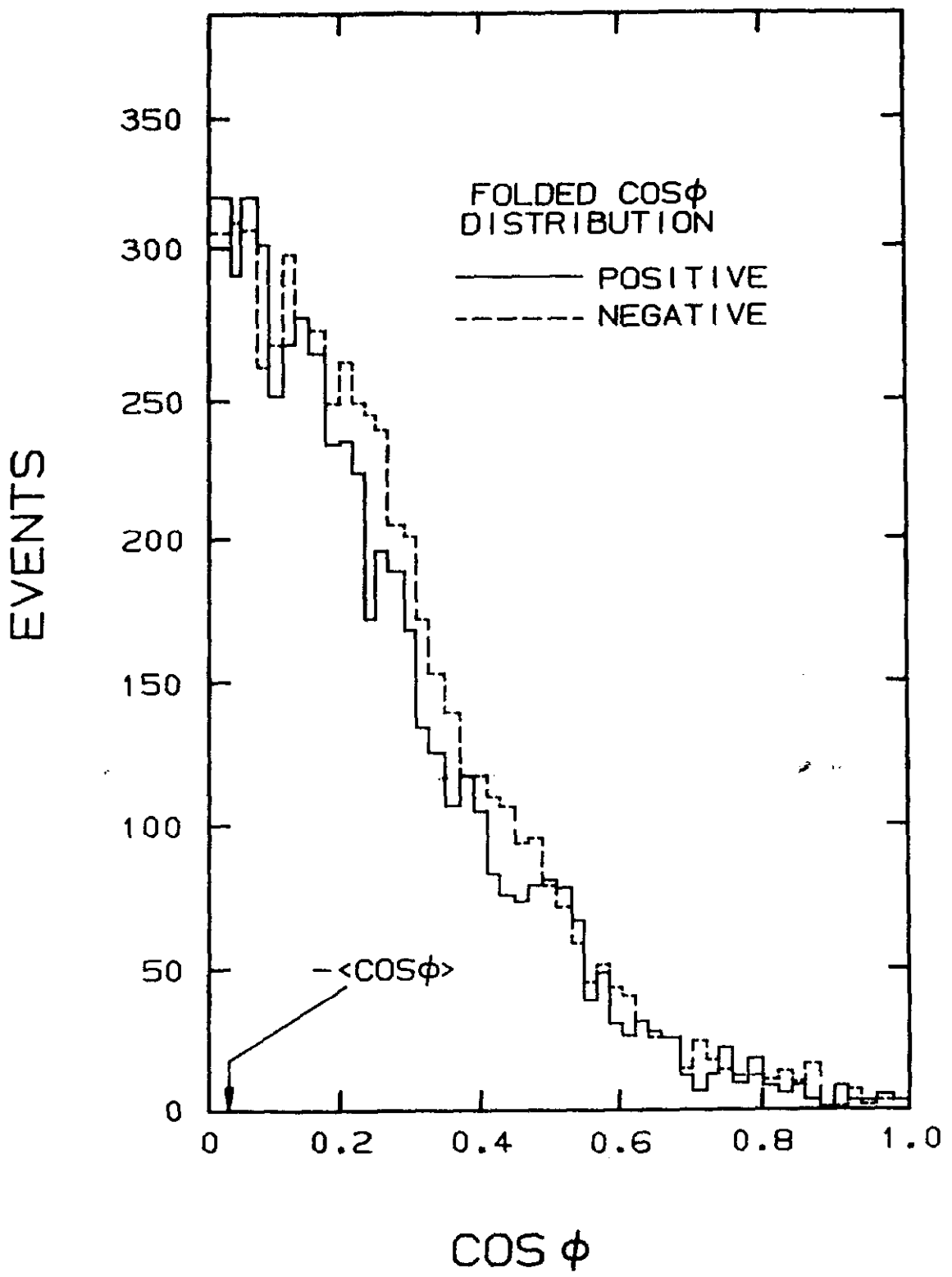

Figure 2

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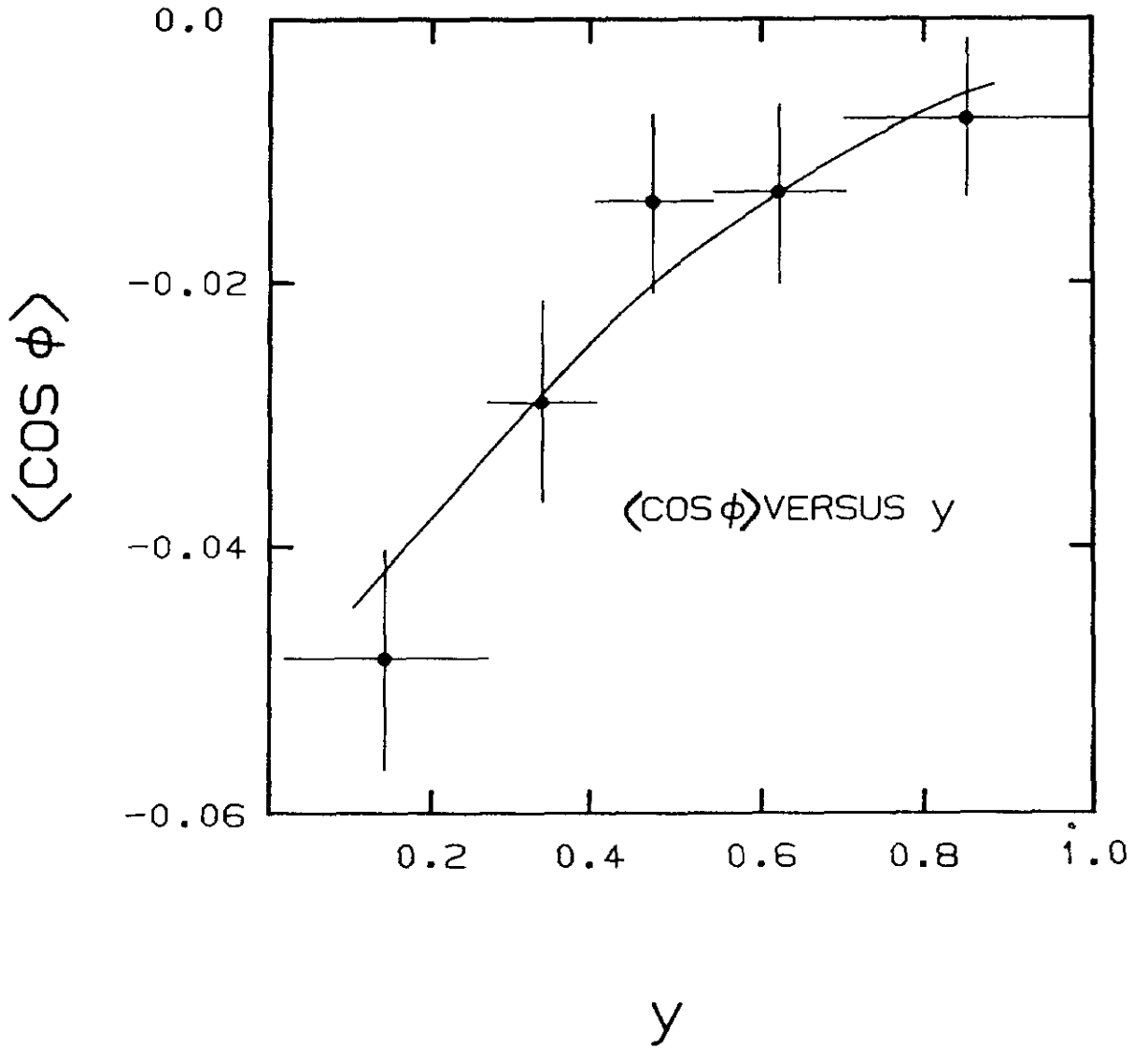

Figure 3

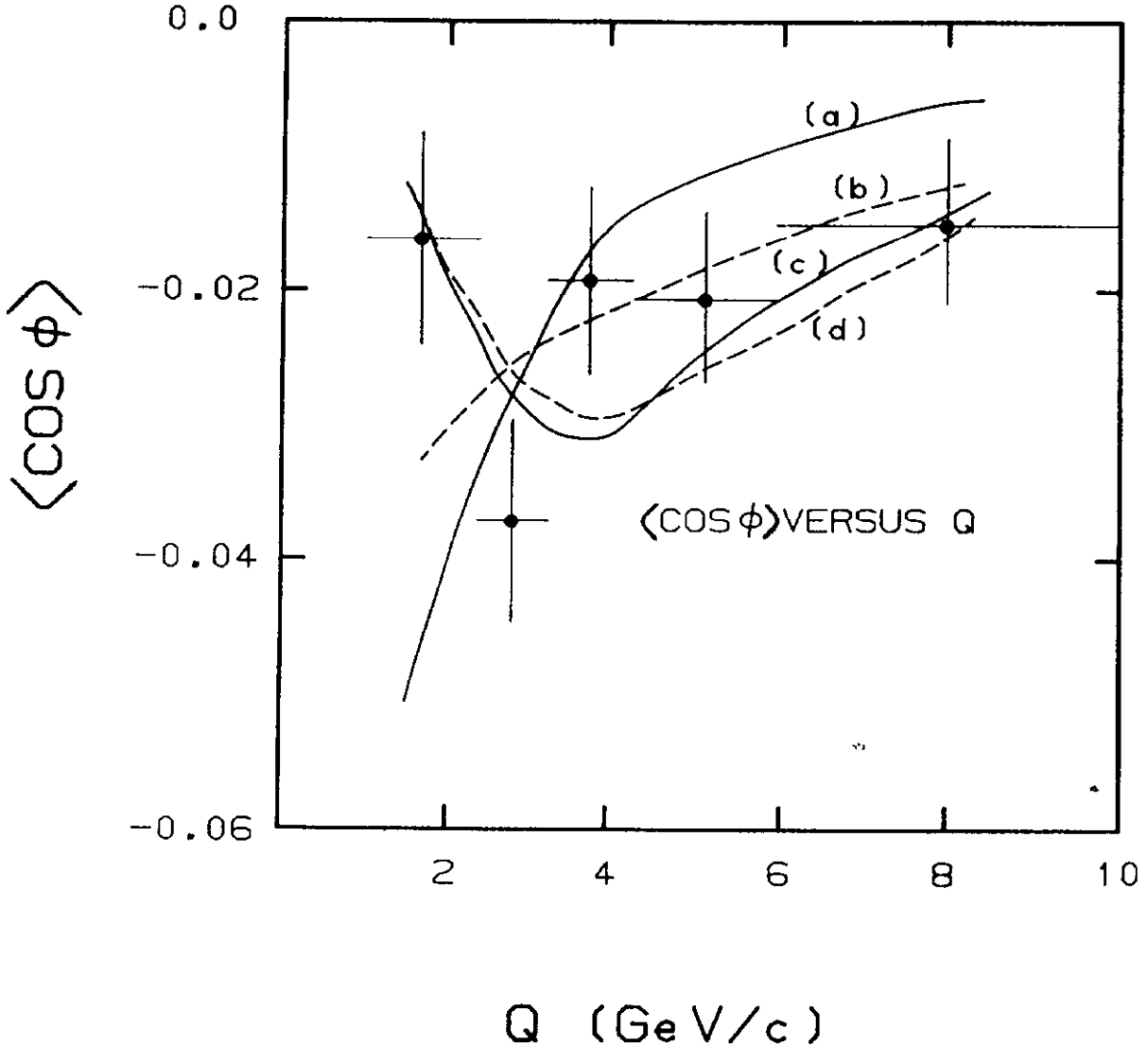

Figure 4